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EXPERIMENTAL INVESTIGATION OF THE EFFECT OF ALUMINUM SIZE AND LOADING ON THE BURNING RATE OF SOLID PROPELLANTS UNDER ACCELERATION

by G. Burton Northam and Wayne P. Jessee

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16. Abstract

Composite polybutadiene acrylic acid (PBAA) propellants were tested under centrifugal acceleration forces directed normal into the burning surface to determine the effect of aluminum particle size and aluminum mass loading on the burning rate. The weight-median diameters of the aluminum powders used in the propellants were 6, 14, and 29 μm; propellants with aluminum mass loadings of 0, 8, and 16 percent were used. The various propellant compositions were tested in a slab motor configuration with a unidirectional burning propellant grain with a 0.5-inch (12.7-mm) web thickness. Centrifuge firings were made at three pressure levels for each of six acceleration levels from static to 280g. Increasing the aluminum particle size from 6 to 29 μm resulted in increased burning rates under acceleration loads directed normal into the propellant surface. Decreasing the aluminum mass loading of the propellant decreased the acceleration sensitivity of the burning rate in the region below 150 and increased the sensitivity in the region above 150g.

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SUMMARY

Composite polybutadiene acrylic acid (PBAA) propellants were tested under centrifugal acceleration forces directed normal into the burning surface to determine the effect of aluminum particle size and aluminum mass loading on the burning rate. The weight-median diameters of the aluminum powders used in the propellants were 6, 14, and 29 μm; propellants with aluminum mass loadings of 0, 8, and 16 percent were used. The various propellant compositions were tested in a slab motor configuration with a unidirectional-burning propellant grain with a 0.5-inch (12.7-mm) web thickness. Centrifuge firings were made at three pressure levels for each of six acceleration levels from static to 280g.

Increasing the aluminum particle size from 6 to 29 μm resulted in increased burning rates under acceleration loads directed normal into the propellant surface. Decreasing the aluminum mass loading of the propellant decreased the acceleration sensitivity of the burning rate in the region below 150 and increased the sensitivity in the region above 150.

INTRODUCTION

During recent years much research has been conducted on the effect which spin-induced, radial acceleration has on solid-propellant combustion with emphasis on the propellant burning rate (refs. 1 to 7). Results from several studies (see, for example, refs.1, 5, 6, and 7) indicate that the burning rate in an acceleration environment is dependent on propellant composition and grain geometry as well as on acceleration level. In general, these studies indicate that many composition variables which affect the static burning rate of propellants will affect the sensitivity of the propellant burning rate to normal acceleration. The studies also indicate that the angle between the acceleration vector and the propellant surface affects the burning rate under acceleration conditions. (The results at an acceleration of 200g showed a maximum increase in rate when the acceleration vector was inclined 90° with respect to the surface and no effect at inclinations of 75° or less.)

Several models (refs. 1 and 8) have been suggested in an attempt to relate the experimental data of these acceleration studies to the combustion process, but the models have been able only to predict trends in burning-rate changes. At the present time it is evident that a better understanding of acceleration effects on the combustion process is necessary before a workable combustion model can be formulated. To gain a better understanding of the acceleration-modified combustion process, a parametric study of the effects of propellant composition and motor geometry is required.

The purpose of this investigation was to systematically determine the effect of aluminum (Al) particle size and aluminum mass loading on the burning rate of a typical polybutadiene acrylic acid (PBAA) composite solid propellant fired under constant normal accelerations into the propellant surface. Unidirectional-burning slabs of composite propellant were fired at low, medium, and high average-pressure levels from 200 psia ($1.38\ MN/m^2$) to 1500 psia ($10.3\ MN/m^2$) and at acceleration levels up to 280g to determine the effect of these two composition variables on the burning rate.

SYMBOLS

a	burning-rate constant in $r = a\left(\frac{p}{500}\right)^n$
g	gravitational constant, 32.2 ft/sec^2 ($9.8\ m/sec^2$)
n	pressure exponent in $r = a\left(\frac{p}{500}\right)^n$
p	average chamber pressure, psia (N/m^2)
r	average burning rate over pressure action time, in./sec (mm/sec)
r_o	average burning rate over pressure action time under static conditions, in./sec (mm/sec)
r/r_o	burning-rate augmentation, rate under acceleration divided by static rate at the same pressure level

APPARATUS AND PROCEDURE

Test Equipment

The propellant slabs were fired in the test motor (see fig. 1(a)), which was mounted on the centrifuge (see fig. 1(b)). This apparatus is described in references 6 and 9. The motor had a 4-inch-wide (101.6-mm) by 6-inch-long (152.3-mm) propellant grain that was 0.5 inch (12.7 mm) thick. This thickness is subsequently referred to as the propellant web. Five sides of the grain were inhibited before the grain was bonded to the lower insert to insure unidirectional burning of the propellant web. A tapered rectangular port which was formed by the upper insert was used to obtain relatively uniform gas velocities along the length of the grain. Use of this motor was advantageous in the determination of the acceleration effects because the effects of gas flow and grain geometry were minimized.

The centrifuge with a 45-inch (1.14-meter) radius was used to apply the nearly constant (0.06-percent variation due to grain regression) acceleration force. The acceleration level was calculated at the center of the 0.5-inch (12.7-mm) web. The motor was mounted on the centrifuge and brought to the desired acceleration level before being fired. All tests were conducted with the acceleration force directed normal into the propellant surface. During the present tests, the motor was mounted with the nozzle in the vertical-up position to minimize the Coriolis forces on the flow field.

Propellant

The propellant compositions tested in this investigation were produced at Langley Research Center and were modifications of an aluminized polybutadiene acrylic acid (PBAA) formulation. The standard propellant had a composition of 70 percent ammonium perchlorate (AP), 16 percent aluminum powder, and 14 percent PBAA binder and curing agent. All of the oxidizer and binder used in the propellants were taken from common lots to minimize batch-to-batch variation. Table I gives the composition of the five propellant batches used. The underground oxidizer had a weight-median particle diameter of 190 μm and the ground oxidizer had a weight-median diameter of 27 μm. The particle size distribution, as determined by sieve analysis, of the unground AP is shown in figure 2; the particle size distribution, as determined by the Micromerograph, of the ground AP is shown in figure 3. (The ratio of unground to ground AP was 1.86.)

Three batches of propellant were used in determining the effect of aluminum-particle-size variation on the burning rate. The composition of these three propellant batches was the same as the standard composition with the only variation being the aluminum particle size. The as-received aluminum powders were classified to give three narrow size ranges with similar distributions in order that particle size could be treated as a discrete variable. The yield of the classification process varied with nominal size, the average yield being about 20 percent. The particle size distributions, as determined by the Coulter Counter, of the three groups of classified aluminum powder are shown in figure 4. The size and the width ratio (diameter at 10 percent divided by diameter at

90 percent (see fig. 4)) of the three classified aluminum powders are listed in the following table:

Weight-median diameter, μm	Width ratio
6	2.6
14	1.9
29	2.0

All three aluminum powder sizes were obtained from the same vendor and manufactured by similar processes. The particle shape was essentially spherical as indicated by analysis of the photomicrographs of the three powders shown in figure 5.

To determine the effect of aluminum mass loading on the burning rate, the percentage of aluminum powder was reduced from the standard 16 percent to 8 percent and to 0 percent. The propellants which contained less than 16 percent aluminum were made by removing either 8 percent or all of the aluminum from the standard composition while maintaining the standard AP/PBAA ratio of 70/14. For the study of varying aluminum content, 14-μm-aluminum formulations were used.

Test Procedure

Five batches of propellant were tested in this investigation; the composition variables of these batches are listed in table I. The results from tests on batches 1, 2, and 3 were compared in order to determine the effect of aluminum particle size on the burning rate of the PBAA propellants fired under steady-state normal acceleration. Test results from batches 2, 4, and 5 were compared in order to determine the effect of aluminum mass loading on the burning rate in an acceleration environment.

The propellants were mixed in an overlapping-wing differential mixer in 100-pound (45.4-kg) batches. After the mix cycle, each batch was deaerated and cast into loaf samples. These samples were cured at 140° F (333° K) for 72 hours in a forced-draft oven. Rough propellant grains were sawed from the loaf samples and the surfaces of the grains were milled to final dimensions of 6 inches (152.4 mm) by 4 inches (101.6 mm) by 0.5 inch (12.7 mm). The web thickness was measured with a micrometer and the grains were inhibited and bonded to the lower inserts.

The low, medium, and high pressure levels resulted from using various nozzle throat diameters. As the burning rate was increased as a result of increased acceleration levels, the pressure experienced for a given nominal nozzle diameter increased. Because of the time involved in data reduction, no attempt was made to maintain constant average pressures as acceleration levels were increased. For each throat diameter, firings were made at normal accelerations of 0g, 20g, 60g, 100g, 200g, and 280g. The slabs were ignited by approximately 30 grains (1.94 grams) of boron potassium nitrate pellets 0.25 inch (6.35 mm) in diameter, which were initiated by a single electrical squib.

The average linear regression rate was determined by dividing the average propellant thickness by the propellant burn time. The burn time for each of the firings was determined from the pressure history by the widely used tangent-bisector method (ref. 10).

A strain-gage pressure transducer was connected to each end of the pellet chamber with a section of steel tubing. The pressure levels were recorded by use of strip-chart recorders at a paper speed of approximately 14 inches per second (0.356 meter per second). The strip-chart record was reduced and the tabulated pressure history was integrated with a computer to determine the average chamber pressure p during motor burning time.

DISCUSSION OF RESULTS

At each acceleration level the average burning rates obtained with the various nozzle throat diameters were fitted by the least-squares method to Vieille's burning rate law $r = a\left(\frac{p}{500}\right)^n$. Figure 6 shows plots of burning rate as a function of pressure for the five propellant batches.

Table II lists the average burning rates and average pressures for the data shown in figure 6. Also listed in table II are the values of burning-rate constant a and the pressure exponent n which resulted from the data fit. As this table indicates, for each propellant batch there were only three to nine firings made at any given acceleration level. Because of this small number of firings, the least-squares fit of the data was sensitive to any random error. It was desirable to make more firings at each acceleration level, but the number of firings was limited by the difficulty in obtaining the specially prepared aluminum.

Although only a limited number of firings were made at each acceleration level, two trends common to all the propellant compositions tested were discernible. For each propellant batch, both the burning-rate constant a and the pressure exponent n increased with increasing acceleration loads.

For comparison of the burning-rate data from the various propellant batches, the burning rates were normalized by using the burning-rate augmentation r/r_0, which is defined as the ratio of the burning rate under normal acceleration to the static burning rate at the same pressure level.

The effect of normal acceleration on the burning-rate augmentation at 500 psia ($3.45\ MN/m^2$) is shown in figures 7 and 8. The variable parameters for these figures are aluminum particle size and aluminum mass loading, respectively.

For the propellants containing 16 percent of either 6-μm or 14-μm aluminum, the augmentation curves shown in figure 7 indicate little increase in r/r_o beyond the 1.28 level reached at 200g. The propellant containing 16 percent of 29-μm aluminum experienced a burning-rate augmentation of 1.60 at 280g with no indication of having reached a maximum. The reduction in r/r_o with the decreasing aluminum diameter indicates the reduction in sensitivity of burning rate to acceleration that can be achieved by using smaller size aluminum. Decreasing the aluminum particle size from 14 to 6 μm resulted in less reduction in r/r_o than did the decrease from 29 to 14 μm. This trend indicates that there may be a limit in the reduction of r/r_o that can be achieved by aluminum-particle-size reduction.

Figure 8 shows the effect of aluminum mass loading on burning-rate augmentation of the PBAA propellants. The aluminized formulations contained 14-μm aluminum. Appreciable rate augmentation was exhibited for the nonaluminized as well as the aluminized propellants. The effect of aluminum percentage was a function of acceleration level. The largest effects of aluminum content occurred at 60g and 280g. Acceleration test levels used were insufficient to define the curves in the region of 60g. At normal accelerations below 100g the 8 percent and 16 percent aluminum additive caused increased augmentation. At 100g the burning-rate augmentation was essentially independent of aluminum content. At normal accelerations above 150g, the rate augmentation decreased as the aluminum content of the propellant increased; at the maximum test acceleration of 280g, the rate augmentation for the nonaluminized propellant was 1.42 as compared with 1.28 for the formulation containing 16 percent aluminum.

Acceleration tests were conducted for the Naval Ordnance Systems Command by the United Technology Center (UTC) using a polybutadiene acrylonitrile (PBAN) propellant at acceleration levels from 10g to 600g (ref. 1). These UTC data showed no increase in burning rate due to accelerations as high as 100g when the aluminum was removed from the control propellant composed of 16 percent aluminum, 68 percent ammonium perchlorate, and 16 percent PBAN. The UTC data also indicated a consistent decrease in burning-rate augmentation with decreasing aluminum content for the range of acceleration loads tested.

The reasons for the different results obtained with the two propellant formulations are not understood. However, the difference between the results obtained in the two programs supports the postulation that acceleration effects are highly dependent on propellant composition.

Examination of the slopes of the burning-rate curves in figure 6 indicates variations in the pressure exponent with acceleration level. This variation in exponent with acceleration was most pronounced in batch 1, the formulation containing 16 percent 6-μm aluminum. At 300 psia $(2.07\ MN/m^2)$ an imposed acceleration load of 280g resulted in a 17-percent increase in burning rate. When the pressure was increased to 1000 psia $(6.89\ MN/m^2)$, a 44-percent increase in burning rate resulted from the 280g normal acceleration. These data indicate the role that pressure can play in the sensitivity of solid propellants to normal acceleration loads and indicate that, at least for some propellant formulations, pressure effects must be considered in any realistic combustion model.

CONCLUDING REMARKS

Five polybutadiene acrylic acid (PBAA) propellants were tested on a ballistic centrifuge to determine the effects of aluminum particle size and aluminum mass loading on burning rate in an acceleration environment. The burning-rate augmentation due to normal acceleration and the effects of pressure on the rate augmentation were dependent on propellant composition and acceleration level. Increasing the aluminum particle size resulted in increased burning-rate augmentations due to acceleration forces directed normal into the burning surface. Thus, reducing the aluminum size appears to be a practical means of minimizing the effect of normal acceleration on burning-rate augmentation.

The burning-rate augmentation was found to be a function of the percentage of aluminum fuel additive in the propellant. The effect of aluminum mass loading on rate augmentation was also found to be a function of normal acceleration level. At normal accelerations below 100g the addition of 8 percent and 16 percent aluminum additive caused increased augmentation as compared with the augmentation for the nonaluminized propellant. At accelerations above 150g the burning-rate augmentation for the nonaluminized propellant was greater than that for the two aluminized formulations.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 5, 1969,
128-32-90-03-23.

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TABLE I. - COMPOSITION AND PROPERTIES OF THE PBAA PROPELLANTS INVESTIGATED

Batch no.	Weight			Al weight-median diameter, μm	Base burning rate at 500 psia (3.45 MN/m^2)		Elongation, percent	Tensile strength	
	Percent PBAA*	Percent AP	Percent Al		in./sec	mm/s		psi	MN/m^2
1	14.0	70.0	16	6	0.285	7.24	29.9	147.8	1.019
2	14.0	70.0	16	14	.264	6.71	31.4	115.6	.797
3	14.0	70.0	16	29	.257	6.53	28.5	105.4	.727
4	15.3	76.7	8	14	.261	6.63	38.7	93.6	.645
5	16.7	83.3	0	---	.230	5.84	41.1	94.7	.653

*This percentage includes the curing agent and catalyst for each batch.

TABLE II.- BURNING-RATE DATA

(a) Batch number 1

Average chamber pressure		Average burning rate		Normal acceleration level, g	a		n
psia	MN/m^2	in./sec	mm/sec		in./sec	mm/sec	
307	2.11	0.247	6.27	0	0.285	7.23	0.278
327	2.25	.258	6.55				
535	3.68	.282	7.16				
559	3.85	.292	7.41				
782	5.39	.314	7.97				
871	6.00	.344	8.73				
306	2.10	.252	6.40	20	.287	7.29	0.283
588	4.05	.292	7.41				
880	6.06	.342	8.68				
299	2.06	.246	6.24	60	.305	7.75	0.434
609	4.19	.326	8.28				
973	6.70	.412	10.46				
339	2.33	.290	7.36	100	.340	8.64	0.427
626	4.31	.368	9.34				
1164	8.02	.491	12.47				
374	2.57	.317	8.05	200	.358	9.09	0.430
835	5.75	.444	11.27				
1302	8.97	.543	13.79				
388	2.67	.328	8.33	280	.361	9.17	0.479
754	5.19	.418	10.61				
1240	8.54	.555	14.09				

TABLE II.- BURNING-RATE DATA – Continued

(b) Batch number 2

Average chamber pressure		Average burning rate		Normal acceleration level, g	a		n
psia	MN/m2	in./sec	mm/sec		in./sec	mm/sec	
282	1.94	0.229	5.82	0	0.264	6.71	0.248
281	1.94	.228	5.80				
249	1.72	.225	5.72				
500	3.45	.266	6.76				
499	3.44	.255	6.48				
729	5.03	.287	7.29				
695	4.79	.240	6.10				
709	4.89	.289	7.34				
734	5.06	.294	7.47				
304	2.10	.240	6.10	20	.273	6.93	0.281
487	3.36	.264	6.71				
724	4.99	.307	7.80				
290	2.00	.245	6.22	60	.303	7.70	0.398
517	3.56	.304	7.72				
854	5.89	.377	9.58				
304	2.10	.254	6.45	100	.310	7.87	0.253
647	4.46	.346	8.79				
962	6.63	.402	10.21				
357	2.46	.300	7.62	200	.338	8.59	0.334
684	4.72	.381	9.68				
997	6.87	.421	10.69				
377	2.60	.305	7.75	280			0.345
778	5.36	.402	10.21				
1065	7.34	.433	11.00				

TABLE II.- BURNING-RATE DATA – Continued

(c) Batch number 3

Average chamber pressure		Average burning rate		Normal acceleration level, g	a		n
psia	MN/m^2	in./sec	mm/sec		in./sec	mm/sec	
240	1.65	0.215	5.46	0	0.257	6.53	0.239
224	1.54	.216	5.49				
444	3.06	.246	6.25				
444	3.06	.251	6.38				
672	4.63	.271	6.88				
691	4.76	.284	7.21				
255	1.76	.222	5.64	20	.262	6.65	.250
519	3.58	.261	6.63				
731	5.04	.290	7.37				
284	1.96	.243	6.17	60	.304	7.72	.387
576	3.97	.325	8.26				
914	6.30	.381	9.68				
314	2.16	.272	6.91	100	.323	8.20	.366
700	4.83	.369	9.37				
927	6.39	.402	10.21				
370	2.55	.314	7.98	200	.352	8.94	.394
799	5.51	.417	10.59				
1336	9.21	.522	13.20				
429	2.96	.388	9.86	280	.410	10.41	.424
868	5.98	.506	12.85				
1523	10.50	.666	16.92				

TABLE II.- BURNING-RATE DATA – Continued

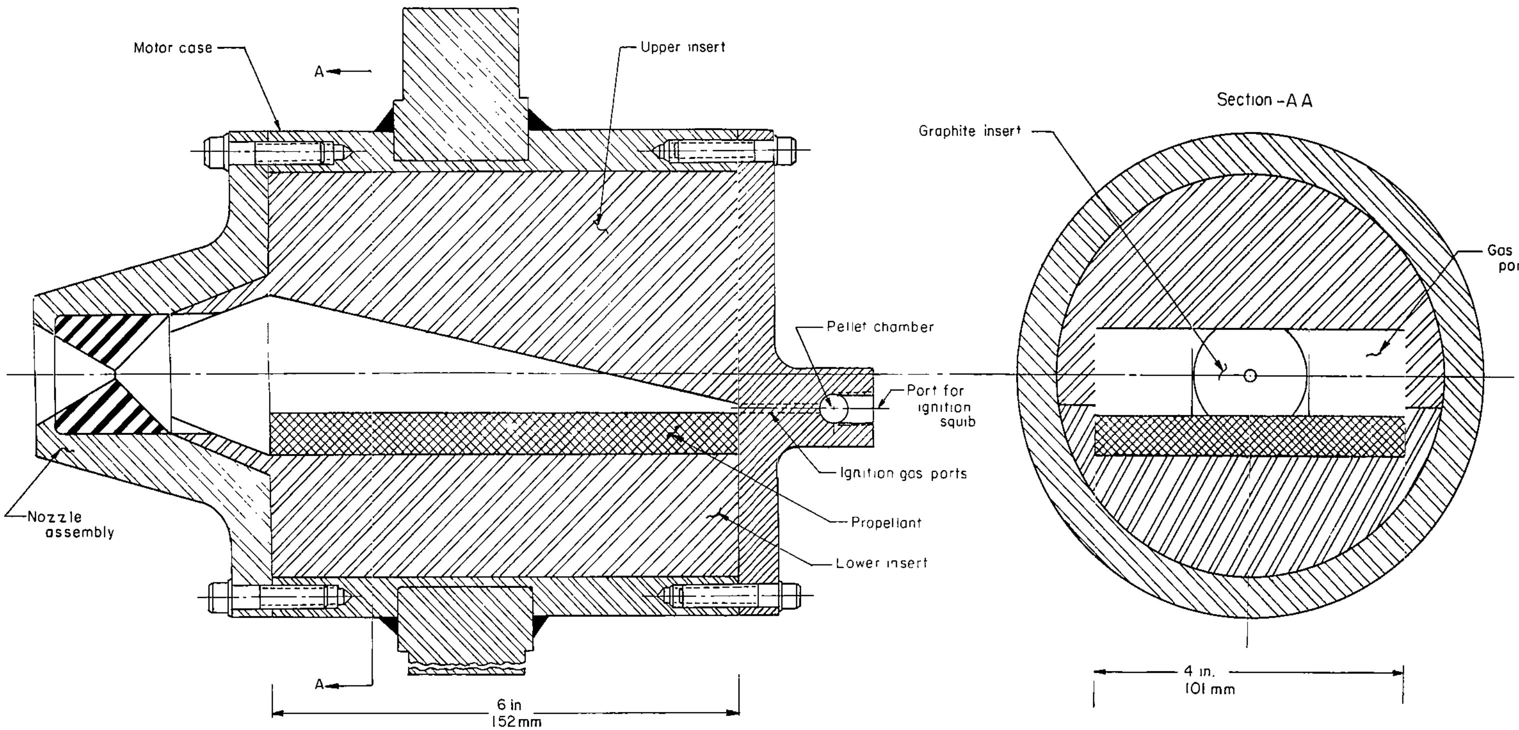
(d) Batch number 4

Average chamber pressure		Average burning rate		Normal acceleration level, g	a		n
psia	MN/m^2	in./sec	mm/sec		in./sec	mm/sec	
261	1.80	0.205	5.21	0	0.261	6.63	0.347
250	1.72	.207	5.26				
505	3.48	.264	6.71				
512	3.53	.265	6.73				
700	4.83	.287	7.29				
713	4.92	.298	7.57				
224	1.54	.190	4.83	20	.260	6.60	.371
220	1.52	.194	4.93				
505	3.48	.265	6.73				
710	4.90	.293	7.44				
204	1.40	.204	5.18	60	.286	7.26	.376
487	3.36	.282	7.16				
760	5.24	.335	8.51				
286	1.97	.242	6.15	100	.305	7.75	.395
422	2.91	.290	7.37				
907	6.25	.384	9.75				
352	2.43	.293	7.44	200	.339	8.61	.403
629	4.34	.378	9.60				
1036	7.14	.452	11.48				
392	2.70	.328	8.33	280	.359	9.12	.382
806	5.56	.428	10.87				
1202	8.29	.504	12.80				

TABLE II.- BURNING-RATE DATA – Concluded

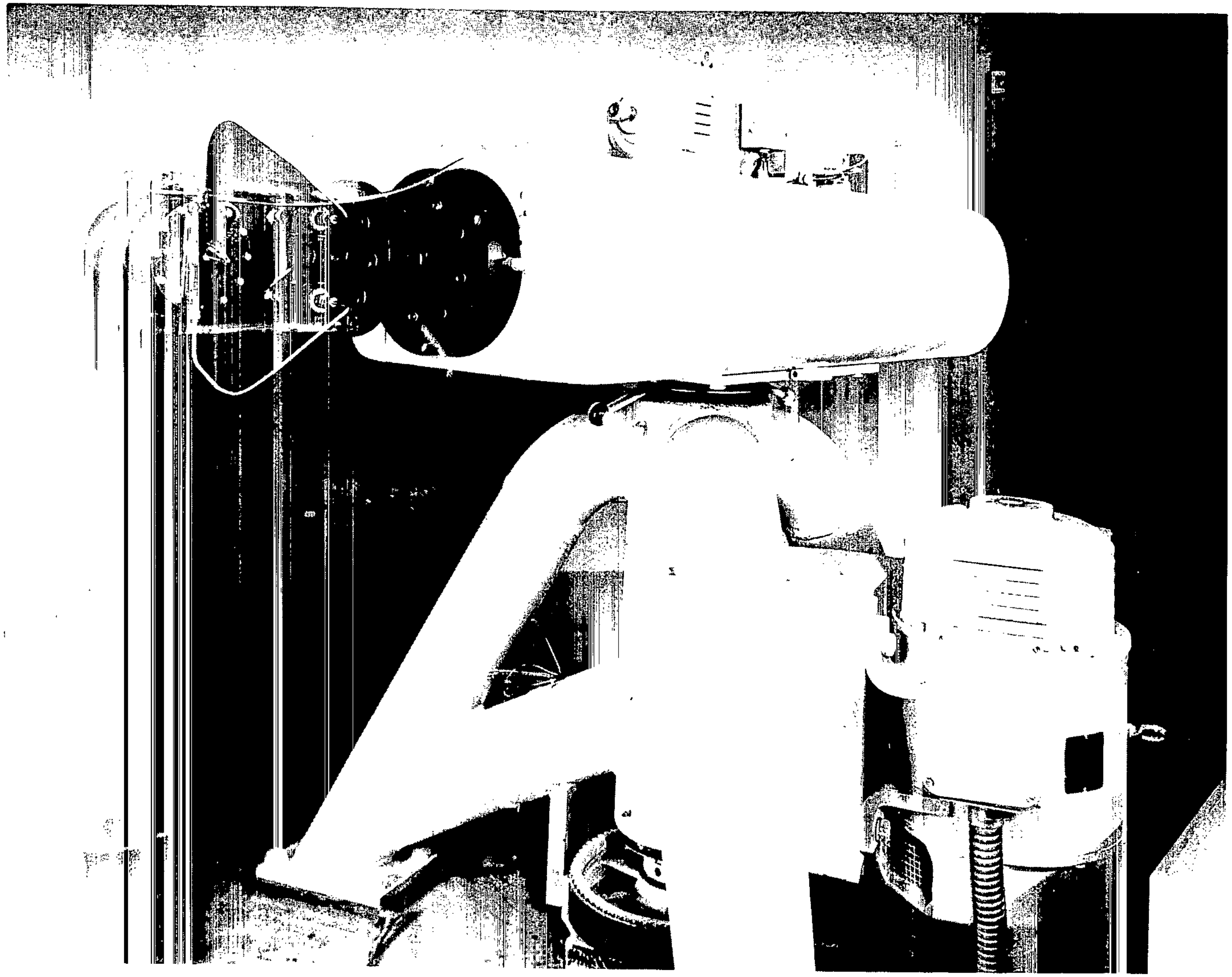
(e) Batch number 5

Average chamber pressure		Average burning rate		Normal acceleration level, g	a		n
psia	MN/m^2	in./sec	mm/sec		in./sec	mm/sec	
204	1.41	0.161	4.08	0	0.230	5.84	0.352
147	1.01	.155	3.94				
367	2.53	.205	5.21				
338	2.33	.194	4.93				
577	3.98	.244	6.20				
558	3.85	.242	6.15				
163	1.12	.154	3.91	20	.234	5.94	.370
377	2.60	.213	5.41				
578	3.99	.245	6.22				
173	1.19	.163	4.14	60	.238	6.05	.354
362	2.50	.214	5.44				
545	3.76	.244	6.20				
170	1.17	.162	4.11	100	.269	6.83	.465
320	2.21	.223	5.66				
561	3.87	.282	7.16				
167	1.15	.178	4.52	200	.304	7.72	.491
411	2.83	.272	6.91				
644	4.44	.347	8.81				
171	1.18	.197	5.00	280	.326	8.28	.473
430	2.96	.301	7.65				
674	4.65	.378	9.60				



(a) Motor cross sections.

Figure 1.- Test apparatus.



(b) Centrifuge.

L-65-2915

Figure 1.- Concluded.

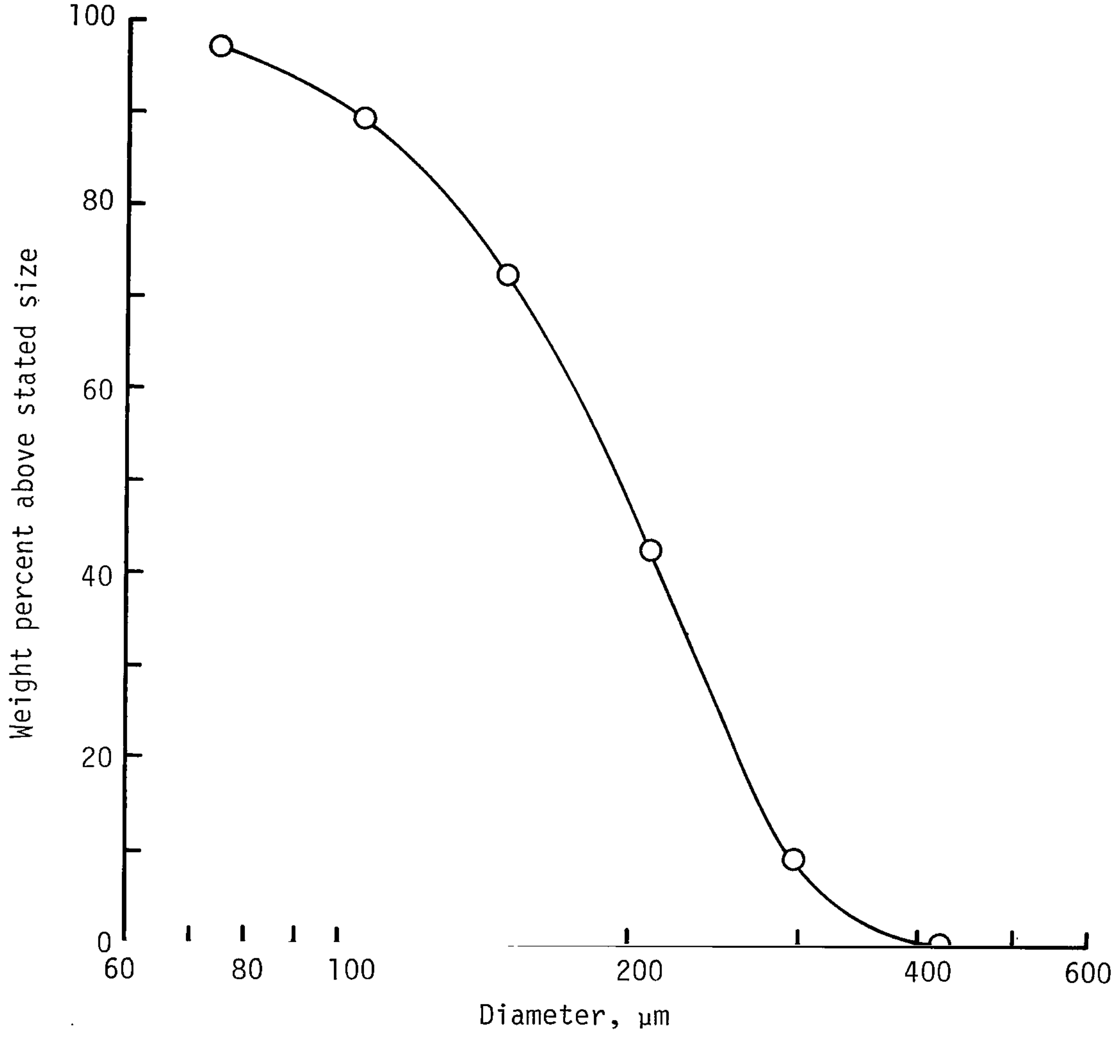


Figure 2.- Unground-oxidizer size distribution.

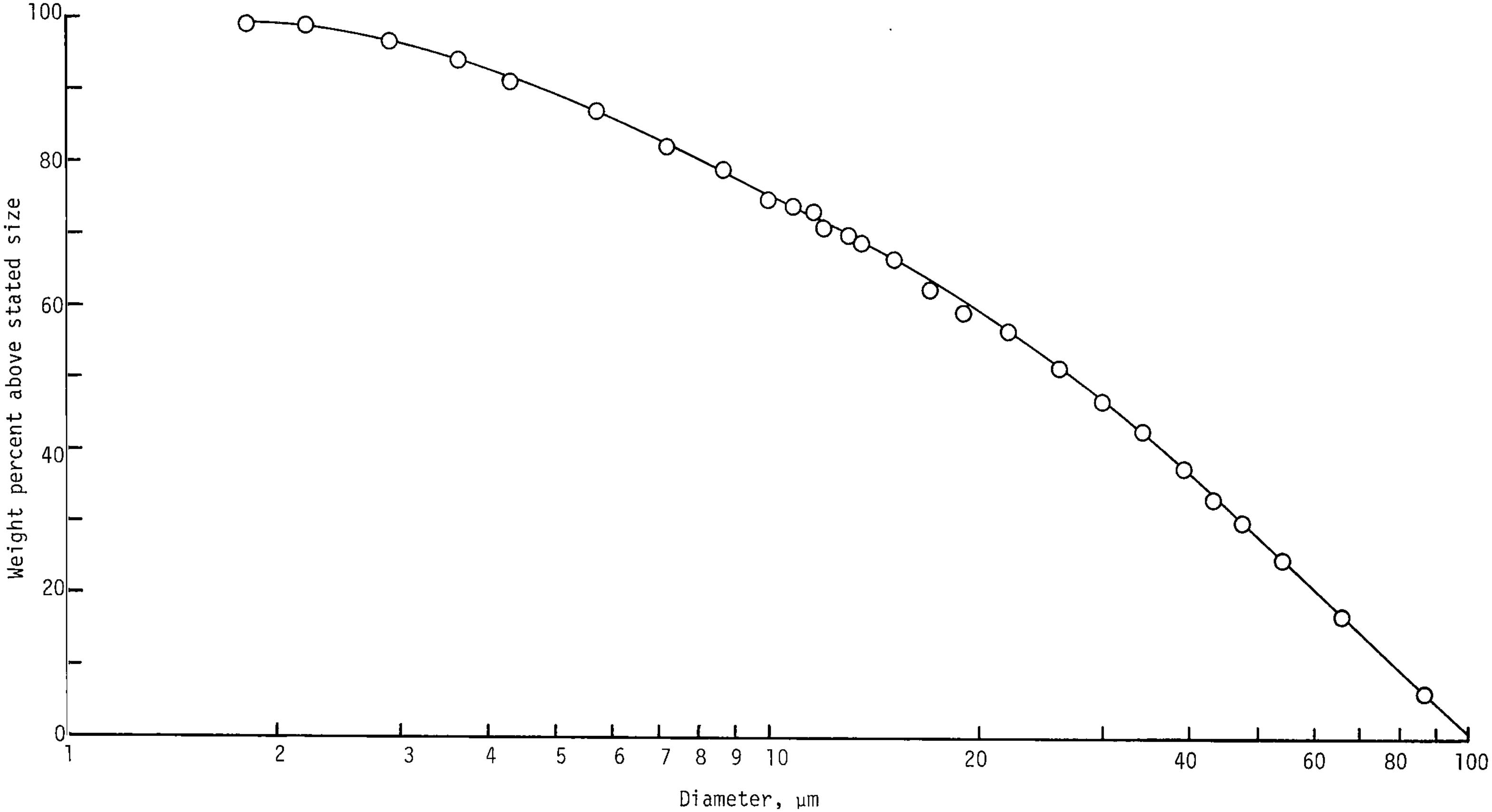


Figure 3.- Ground-oxidizer size distribution.

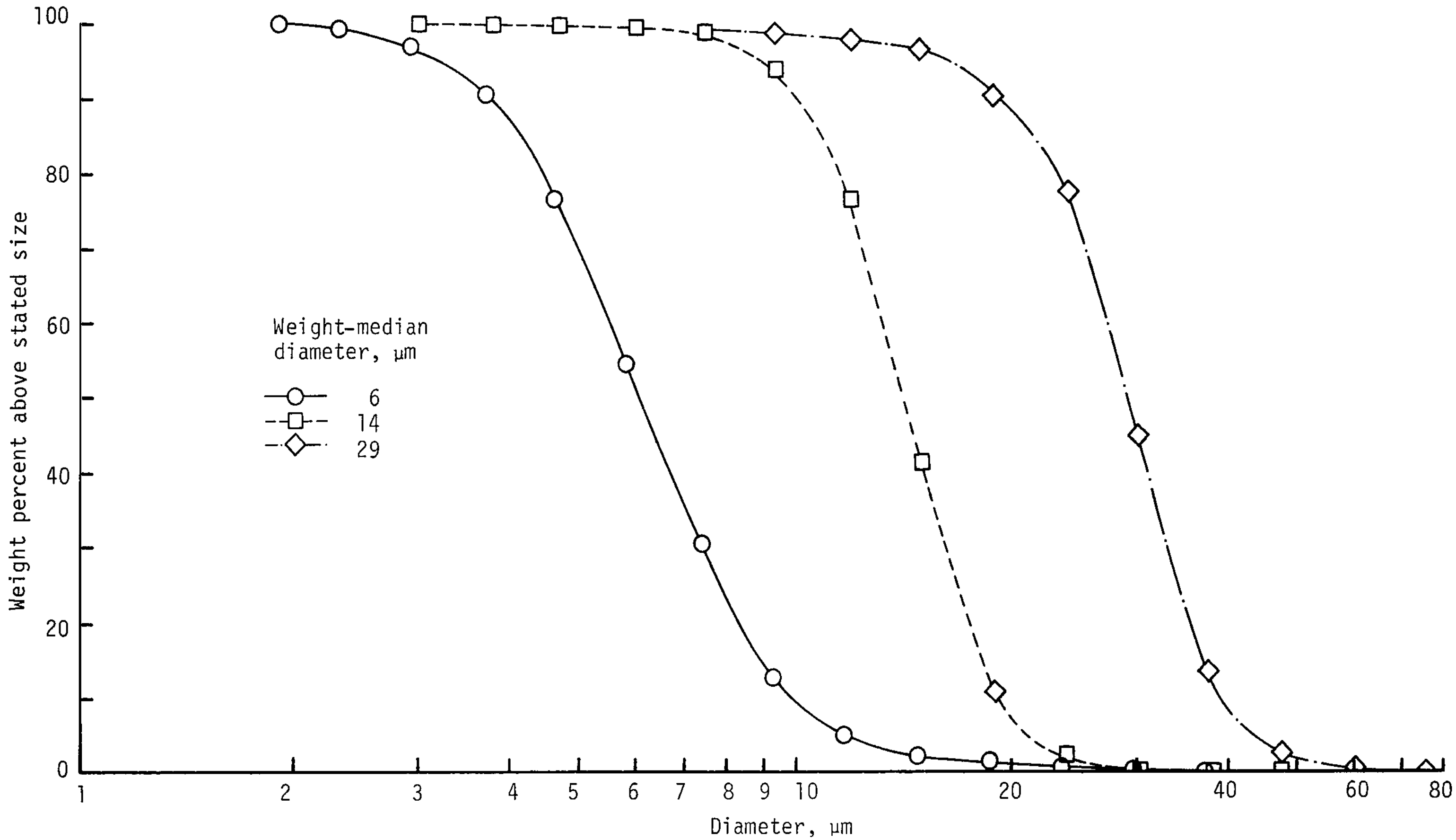
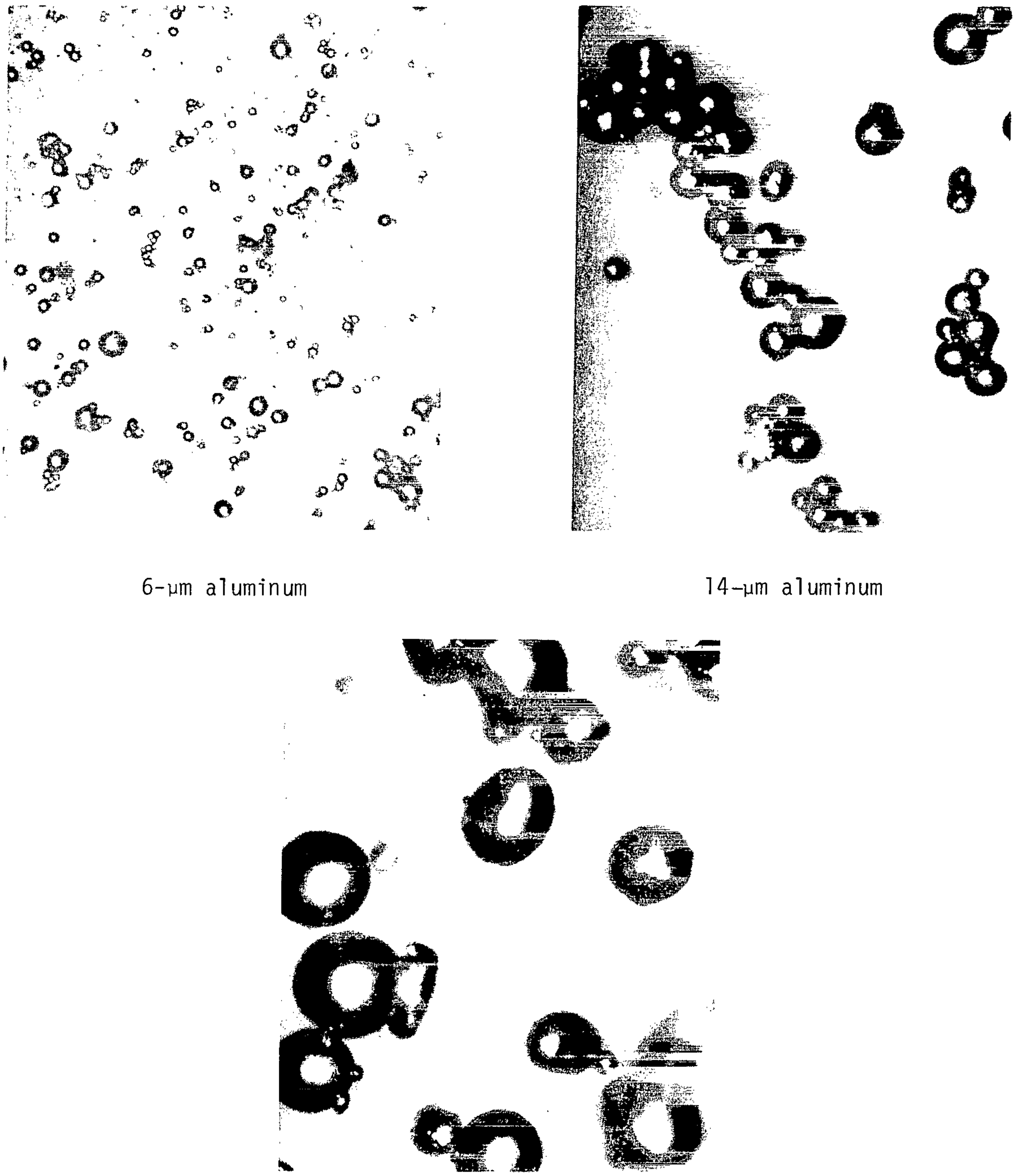


Figure 4.- Aluminum particle-size distributions.



6-µm aluminum

14-µm aluminum

29-µm aluminum

Figure 5.- Photomicrographs of the aluminum powders.

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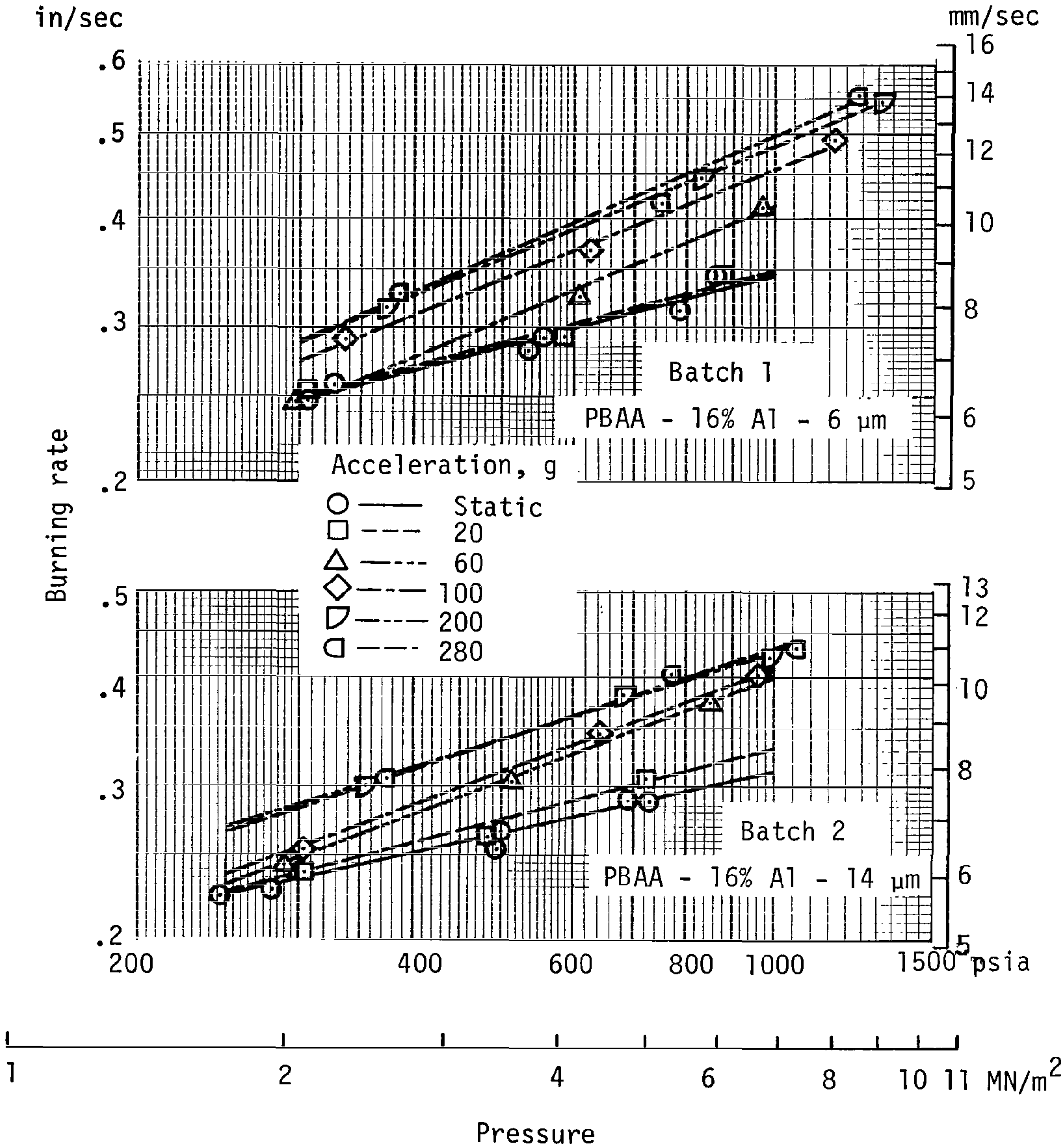

Figure 6.- Burning-rate data for the five propellant batches.

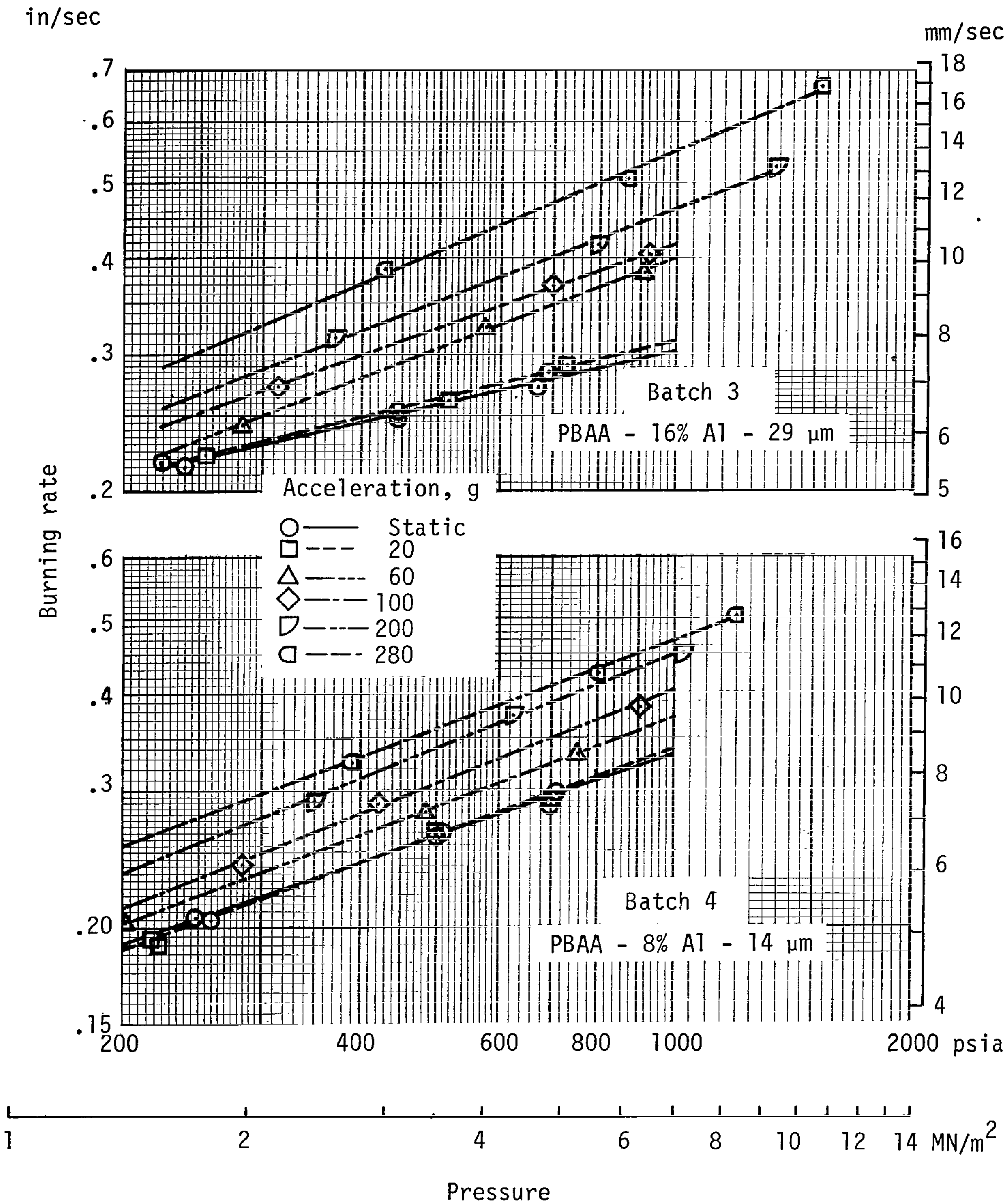

Figure 6.- Continued.

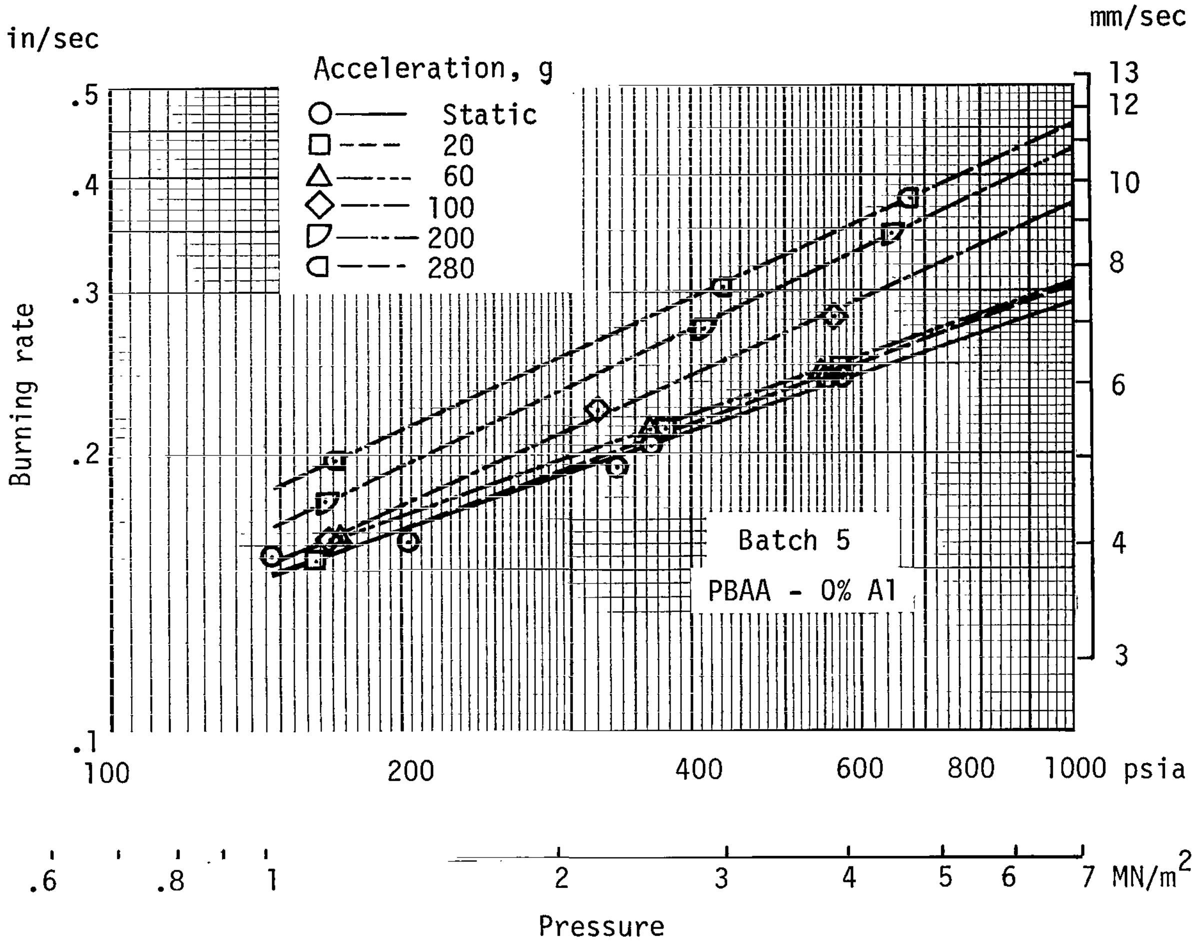

Figure 6.- Concluded.

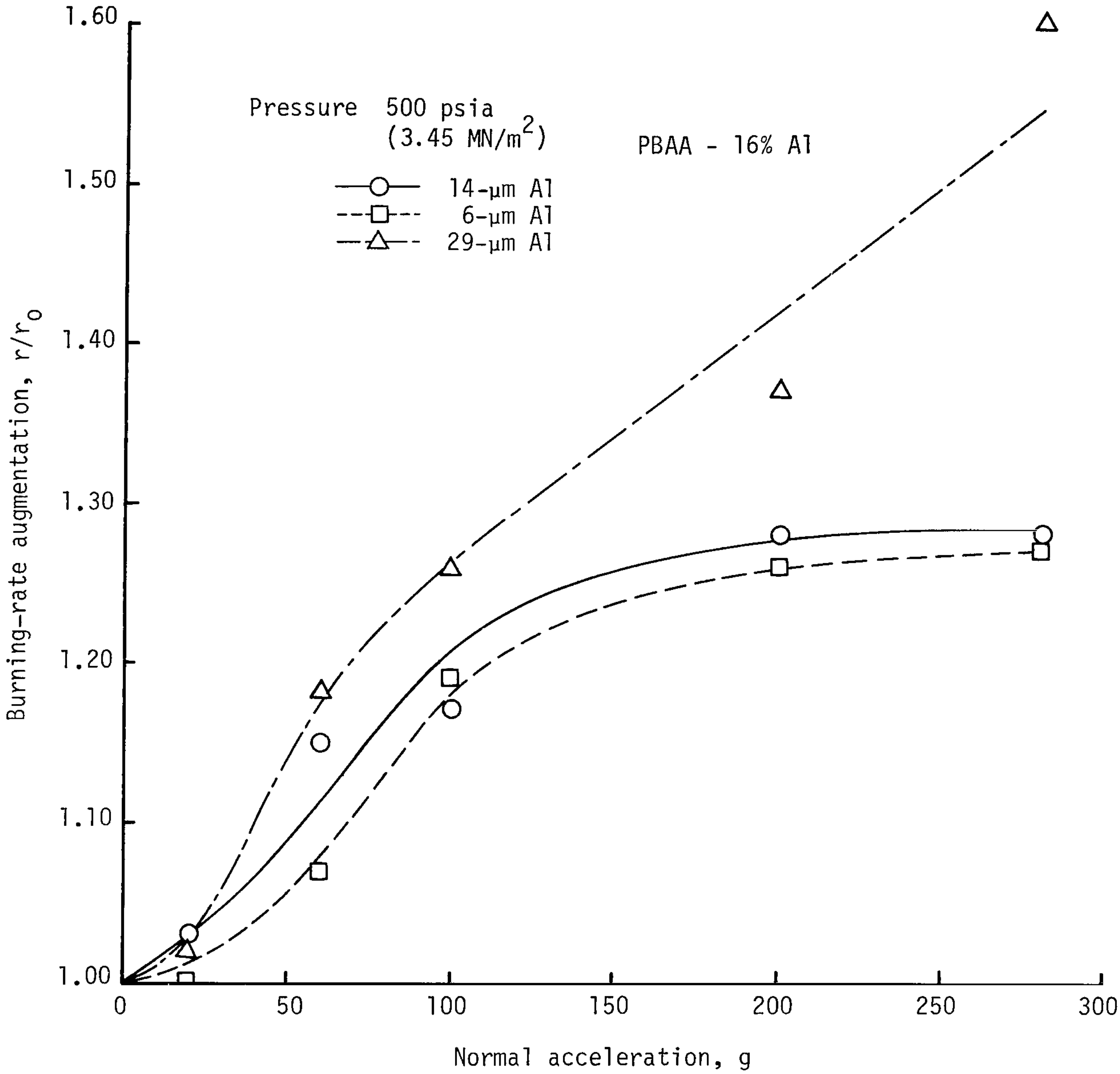

Figure 7.- Effect of acceleration on burning-rate augmentation for various aluminum particle sizes.

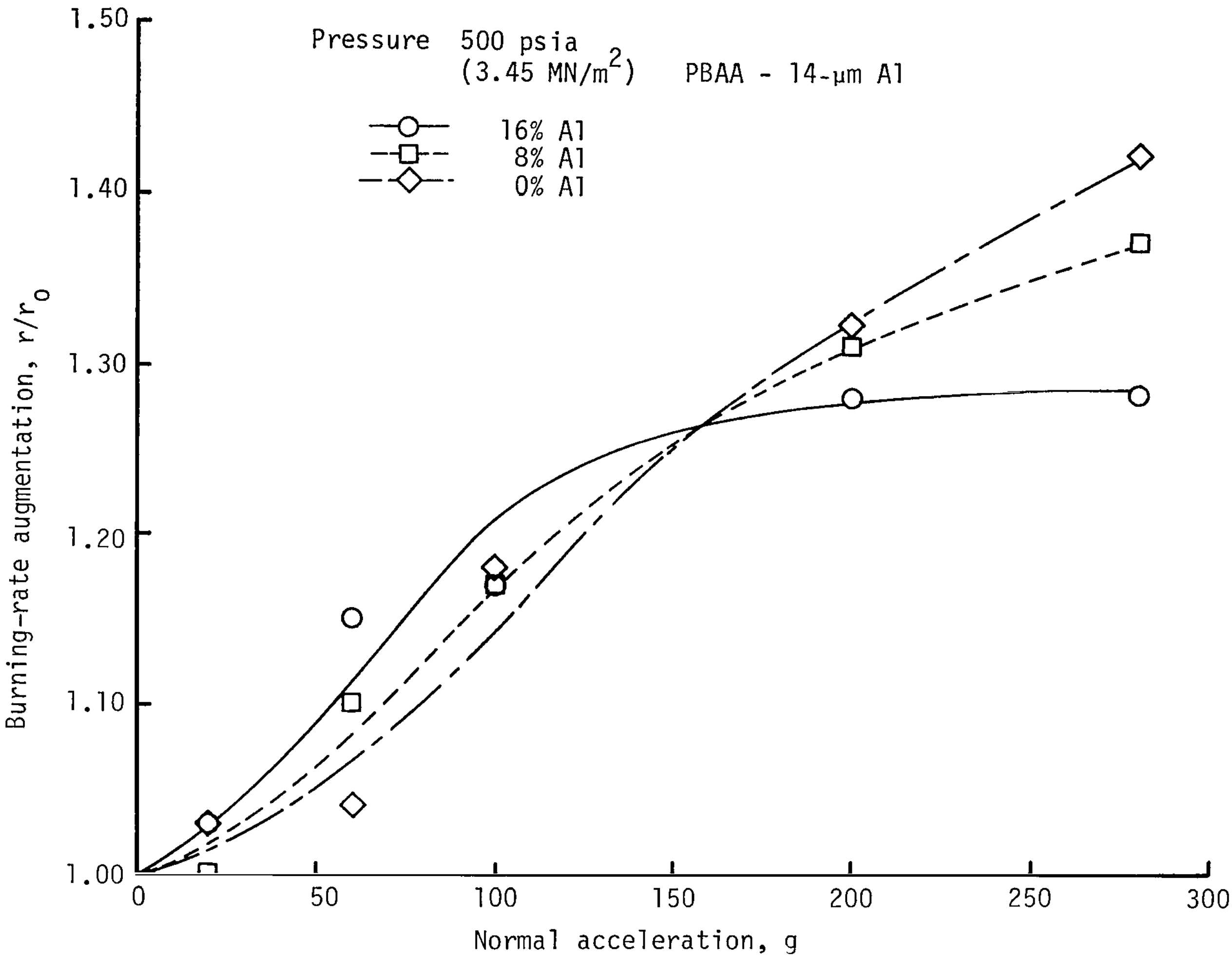

Figure 8.- Effect of acceleration on burning-rate augmentation for various aluminum mass loadings.

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